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Far-reaching effects of Tibetan warming amplification on polar sea-ice retreat

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Mian Xu¹, Shichang Kang², Haijun Yang³, James A. Screen⁴, Zhenming Ji¹✉, Yannick Peings⁵, Junhua Yang¹, Yuling Hu¹, Xintong Chen¹ & Hao Yu⁴

The polar regions are projected to warm faster than the global average, known as polar amplification, which have been extensively investigated. Warming amplification is also projected at high altitudes, particularly over the Tibetan Plateau. However, little is known about the influence of Tibetan Plateau amplification on the wider climate systems, including polar sea-ice. Here, using numerical simulations, we show Tibetan Plateau amplification accounts for ~20–30% and ~10–15% of the Arctic and Antarctic sea-ice loss, respectively, projected under a high-emission scenario. Notably, the relative contribution of Tibetan Plateau amplification to projected sea-ice loss increases with the level of global warming. For the Arctic, Tibetan Plateau amplification primarily drives sea-ice loss by enhancing northward atmospheric heat transport. For the Antarctic, a two-stage ocean-atmosphere-coupled pathway is proposed: the enhanced southward oceanic heat transport warms the southern low-to-mid-latitude sea-surface temperatures, which subsequently modify the large-scale atmospheric circulation, favorable for Antarctic warming and sea-ice loss.

Since the Industrial Revolution, Earth has experienced a rapid and sustained warming trend, and is now projected to reach—and soon exceed—the 1.5 °C threshold set by the Paris Agreement^{1–3}. The projected warming is not spatially uniform, most pronounced at the poles and in high-altitude regions, particularly the Tibetan Plateau (TP), a phenomenon commonly referred to as warming amplification^{4–6}. While the causes and consequences of the projected Arctic and Antarctic amplifications—especially in the Arctic—have been extensively explored over the past few decades^{7,8}, the potential global influence of the Tibetan Plateau amplification (TPA) has received far less attention.

Commonly known as the Earth's Third Pole, the TP plays a pivotal role in shaping global weather and climate through both mechanical and thermal processes. Mechanically, the TP influences climate primarily in winter by splitting the mid-latitude westerly jet into two branches along its northern and southern flanks, thereby exerting a strong impact on downstream weather and climate systems^{9–11}. Its orographic features also modulate global ocean circulation, including the global meridional overturning circulation and the variability of the El Niño–Southern Oscillation^{12–14}. Thermally, the TP exerts a strong influence on climate—particularly the Asian summer monsoon—via its sensible-heat-driven air-pump effect^{15–17}.

In recent decades, the TP has experienced a faster warming rate than the global average, although still weaker than that observed over the Arctic^{5,18}. Recent studies have revealed the influence of the TPA on the East Asian precipitation patterns¹⁹ and tropical cyclone activity in the western North Pacific²⁰. Importantly, the climatic influence of the TPA is not confined to the downstream Asian-Pacific region and even extends to the two poles. Particularly, the latest literature unveiled the atmospheric resonance between the TPA and Arctic amplification^{21,22}. Nonetheless, to what extent the TPA under different emission scenarios contributes to polar sea-ice retreat remains largely unexplored. Moreover, compared with its Arctic counterpart, how the TPA influences the Antarctic sea ice is less clear. Answering these questions is critical to improve our understanding of the rapid sea-ice decline both in observations and climate model projections^{23,24}.

Using a suite of climate model simulations, this study isolates and quantifies the contribution of the TPA to the sea-ice retreat over the Arctic and Antarctic and unravels the underlying dynamical mechanisms. Our findings offer valuable insights into the climatic linkages between the TP and the other two poles under global warming, and contribute to a better understanding of the potential risks associated with climate-induced changes in polar environments^{25–27}.

¹State Key Laboratory of Cryospheric Science and Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China. ²Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China. ³Department of Atmospheric and Oceanic Sciences and Key Laboratory of Polar Atmosphere-ocean-ice System for Weather and Climate of the Ministry of Education, Fudan University, Shanghai, China. ⁴Department of Mathematics and Statistics, University of Exeter, Exeter, UK. ⁵Department of Earth System Science, University of California, Irvine, Irvine, CA, USA. ✉e-mail: jizhenming@nieer.ac.cn

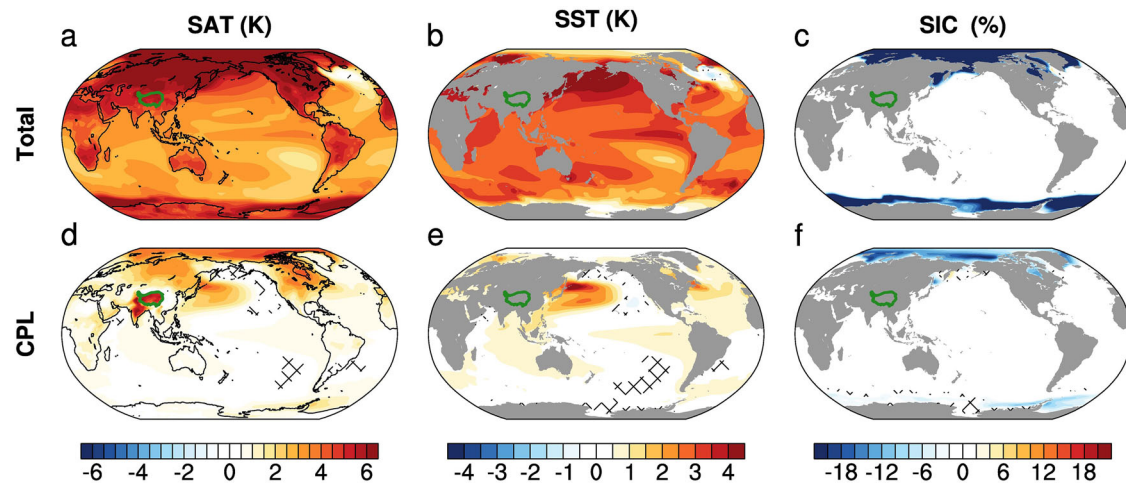


Fig. 1 | Climate responses to global warming and the TPA. Differences in annual-mean (a) near-surface temperature (SAT; K), (b) sea-surface temperature (SST), and (c) sea-ice concentration (SIC; %) between the end-of-century period (2080–2099; RCP85) and the historical period (1986–2005; HIST), based on ensemble transient fully-coupled simulations. d–f are the same as (a–c), but for the responses to the

Tibetan Plateau amplification (TPA), derived from the TP-nudged fully-coupled simulations (TP_HIST and TP_RCP85). Cross-hatching indicates regions where anomalies are not statistically significant at the 95% confidence level based on a grid-point-wise bootstrap resampling statistical test.

Results

How much the TPA contributes to Arctic and Antarctic sea-ice retreat?

A pair of fully-coupled present-day and future transient simulations, including all forcings, and a pair of time-slice simulations with the atmosphere over the TP (outlined by green line in Fig. 1) nudged towards its present-day and future states, respectively, are performed using the Community Earth System Model (CESM; see “Methods”). Based on these simulations, the climate responses to global warming under Representative Concentration Pathways 8.5 (RCP8.5) and in response to TPA alone are compared with each other (Fig. 1). Despite much weaker in magnitude, the TPA also induces a global-scale warming, particularly in the Northern Hemisphere, with the SST responses displaying a similar pattern as in the total response to global warming (Fig. 1a, b, d, e). In this study, four sea-ice metrics are applied in this study, i.e., sea-ice concentration (SIC), sea-ice thickness (SIT), sea-ice extent (SIE), and sea-ice volume (SIV), with the first two depicting the spatial distribution of sea-ice, while the last two estimating the total amount of sea-ice over the two poles (Methods). The TPA-induced asymmetric warming over the two poles causes SIC reduction over the pan-Arctic and around the Antarctic Peninsula (Fig. 1c, f).

Figure 2 gives a closer look at the TPA-induced sea-ice loss. Another pair of partially-coupled simulations was performed, with the full ocean model replaced by a single-layer slab ocean model (SOM; see “Methods”). Since in this model the ocean is treated as motionless, only energy exchange upon the ocean-atmosphere interface is considered, which allows us to examine the importance of ocean dynamics in the response to TPA. Note here that a different convention is used to denote statistically significant results (black stippling), while in Fig. 1, cross-hatching is used to denote non-significant results, for clarity of the figure. This marking scheme is applied to the remaining figures. The TPA-induced reduction in Arctic sea-ice concentration (SIC) is most pronounced in the Barents-Kara Seas, East Siberian Sea and Chukchi Sea (Fig. 2a), resembling—although with a weaker amplitude—that associated with global warming (Supplementary Fig. 1a). The magnitude of Arctic SIC decline in the SOM simulations is comparable to that in the fully-coupled simulations (Fig. 2b). The TPA accounts for approximately 26.7% of the total Arctic sea-ice extent (SIE) loss under RCP8.5, which decreases to about 19.9% when ocean dynamics is excluded (Fig. 3a). This suggests that ocean circulation adjustment in response to the TPA plays a limited role in the TPA-induced Arctic SIC reduction.

The spatial distribution of Arctic sea-ice thickness (SIT) reduction induced by the TPA (Fig. 2e, f) also mirrors that from global warming

(Supplementary Fig. 1c). However, the SIT reduction in the SOM simulations is obviously smaller than in the fully-coupled ones. The contribution of the TPA to Arctic sea-ice volume (SIV) loss drops from 32.5% in the fully-coupled simulations to 15.9% in the SOM simulations (Fig. 3c), likely reflecting the higher sensitivity of SIV, compared with SIE, to changes in ocean dynamics^{28,29}.

The magnitude of Antarctic SIC reduction due to global warming is generally weaker than that in the Arctic (Supplementary Fig. 1b). Antarctic SIC decline induced by the TPA in the fully-coupled simulations maximizes over the Bellingshausen Sea and Weddell Sea (Fig. 2c). In contrast, in the SOM simulations SIC decline is only found over the Weddell Sea, and with a lesser magnitude as in the fully-coupled runs (Fig. 2d). The relative contribution of the TPA to Antarctic SIE reduction drops substantially from 15.1% in the fully-coupled simulations to approximately 3.3% in the SOM simulations (Fig. 3b). This suggests that ocean circulation adjustment in response to the TPA plays a dominant role in the TPA-induced Antarctic sea-ice loss.

A similar pattern is observed for Antarctic SIT reduction (Figs. 2g, h, 3d). Furthermore, it is noteworthy that the relative contribution of the TPA to both SIE and SIV loss increases with the level of global warming (red lines in Fig. 3). Specifically, the relative contribution of TPA to Arctic SIE and SIV loss increases from ~20% under RCP2.6 and RCP4.5 scenarios to ~30% under RCP8.5 scenarios, and from ~10% to ~15% for its Antarctic counterpart. This could be partially attributed to a stronger TPA signal in a warmer climate: the TPA index—defined as the ratio of the TP surface warming (area-weighted over the region outlined by the green line in Fig. 1) to global-mean surface warming—increases from 1.11 to 1.33 and 1.38 under RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively (Supplementary Fig. 2).

How the TPA induces Arctic and Antarctic sea-ice retreat?

Changes in poleward heat transport play a crucial role in polar warming and sea-ice retreat^{30,31}. To assess the influence of the TPA on meridional heat transport, we first note that sea-ice loss itself can feedback on heat transport patterns^{32,33}. To remove this confounding effect, we conducted another pair of TP-nudged fully-coupled CESM simulations, in which sea-ice was also nudged towards its historical climatology (TP+ sea-ice-nudged fully-coupled runs; see “Methods”). Moreover, a pair of TP-nudged atmosphere-only time-slice simulations, with SST/SIC conditions fixed at the year 2000 level, is performed to check the TPA’s influence on atmospheric heat transport (AHT) in the absence of surface boundary changes.

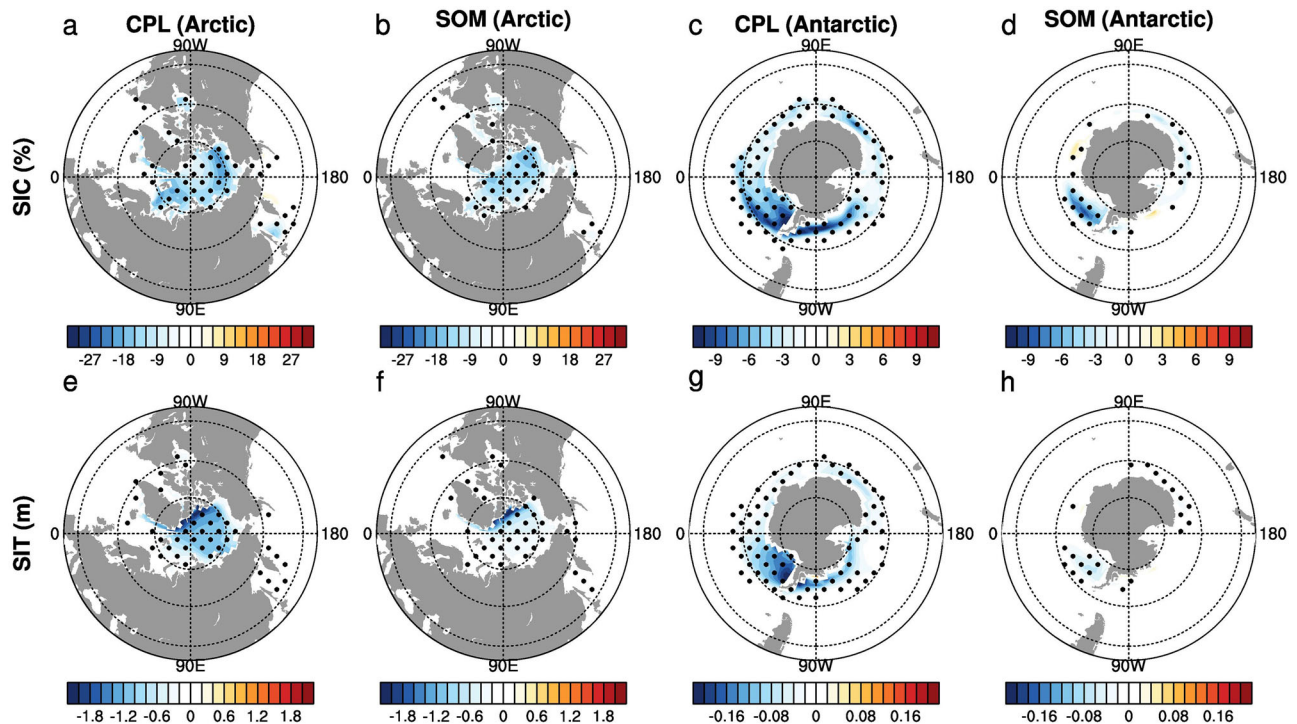


Fig. 2 | Sea-ice retreat induced by the TPA. **a** Annual-mean changes in Arctic sea-ice concentration (SIC; %) in response to the TPA, derived from fully-coupled CESM simulations (TP_RCP85 minus TP_HIST). **b** Same as **a**, but from partially-coupled simulations with a slab ocean model (TP_RCP85_SOM minus TP_HIST_SOM).

c, d Same as (**a, b**), but for Antarctic SIC. **e–h** Same as (**a–d**), but for changes in sea-ice thickness (SIT; m). Black stippling indicates regions where anomalies are statistically significant at the 95% confidence level based on a grid-point-wise bootstrap resampling statistical test.

The TPA enhances the total poleward heat transport (THT) into the Arctic and, to a lesser extent, into the Antarctic (Fig. 4a). Although the TPA also increases poleward oceanic heat transport (OHT) near 60°N, its magnitude is considerably smaller than that of AHT, and it is also weaker than the AHT response in the atmosphere-only simulations. This supports the earlier conclusion that ocean dynamics plays a minimal role in Arctic sea-ice retreat induced by the TPA.

Interestingly, while the TPA-induced enhancement of southward OHT exceeds that of AHT in the southern low-to-mid latitudes, it is surpassed by AHT near 60°S. This suggests that, although ocean circulation adjustments to the TPA are important, they may not directly drive Antarctic sea-ice loss. This hypothesis will be further explored in the following section.

To further elucidate the mechanisms behind the meridional heat transport response, the AHT responses are further decomposed into four components: mean dry static energy (MDSE), mean latent energy (MLE), eddy dry static energy (EDSE), and eddy latent energy (ELE) (Fig. 4b, d). The EDSE dominates the northward AHT into the Arctic, while the MLE and ELE—representing moisture transport—also modestly contribute. In contrast, the MDSE exhibits a negative contribution relative to the other components. This suggests that the TPA enhances the northward transport of both dry static energy and water vapor primarily through strengthening poleward-propagating eddies, ultimately contributing to Arctic warming and sea-ice loss.

For OHT, the responses are decomposed by ocean basins—namely, the Atlantic, Pacific, and Indian Oceans (Fig. 4c). The enhanced OHT into the Arctic is primarily attributed to the Atlantic Ocean. In contrast, the Pacific Ocean dominates the increase in southward OHT across the southern low-to-mid latitudes, while the Indian Ocean contributes minimally.

Next, we investigate the mechanisms through which the TPA induces sea-ice retreat in the Arctic and Antarctic. Given the known seasonality in the polar climate responses to the TP warming³⁴, we first examine the seasonal cycles of the TPA-induced surface warming over both poles (Supplementary Fig. 3). The TPA-induced Arctic surface warming

maximizes in boreal autumn (September–October–November), rather than in boreal winter (December–January–February) (Supplementary Fig. 3a). This might be partly attributed to a strengthening of the northern stratospheric polar vortex (SPV) during winter, associated with a reduction in upward-propagating planetary waves (Supplementary Fig. 4a, b). Downward extension of the SPV anomaly induces an acceleration of the northern westerly jet throughout the whole troposphere (Supplementary Fig. 4c, d), which counteracts polar warming³⁵.

In contrast, the TPA-induced Antarctic surface warming maximizes during austral winter (June–July–August) in both the sea-ice-free-running and sea-ice-nudged fully-coupled simulations. However, the atmosphere-only simulations exhibit little to no warming signal over the Antarctic (Supplementary Fig. 3b), consistent with the earlier finding that ocean dynamics play a dominant role in Antarctic sea-ice loss induced by the TPA. Seasonal breakdown of sea-ice responses (Supplementary Tab. 1) is overall consistent with the surface warming signal. Nonetheless, to make the quantification analysis for the two poles comparable and intuitive, the quantitative results above are based on annualized metrics, while the following mechanism diagnosis will focus on boreal autumn for the Arctic and austral winter for the Antarctic, respectively.

Strong TPA enhances the meridional temperature gradient across the northern mid-to-high latitudes, prompting a poleward shift of the westerly jet stream (Fig. 5a, d). According to linear wave theory, poleward-propagating eddies are constrained by their critical lines—regions where the zonal-mean wind equals the eddy phase speed^{36,37}. As the westerly jet shifts northward, the associated eddy activity, characterized by storm tracks, is also displaced towards higher latitudes (Fig. 5b, e). This supports the earlier finding that the EDSE transport plays a dominant role in the northward AHT into the Arctic (Fig. 4b, d). The intensified poleward-propagating eddies enhance the transport of both dry static energy and water vapor into the Arctic, thereby prompting the Arctic surface warming (Fig. 5c, f) and contributing to sea-ice loss. The Arctic warming pattern derived from the atmosphere-only simulations is consistent with that from the TP+sea-ice-

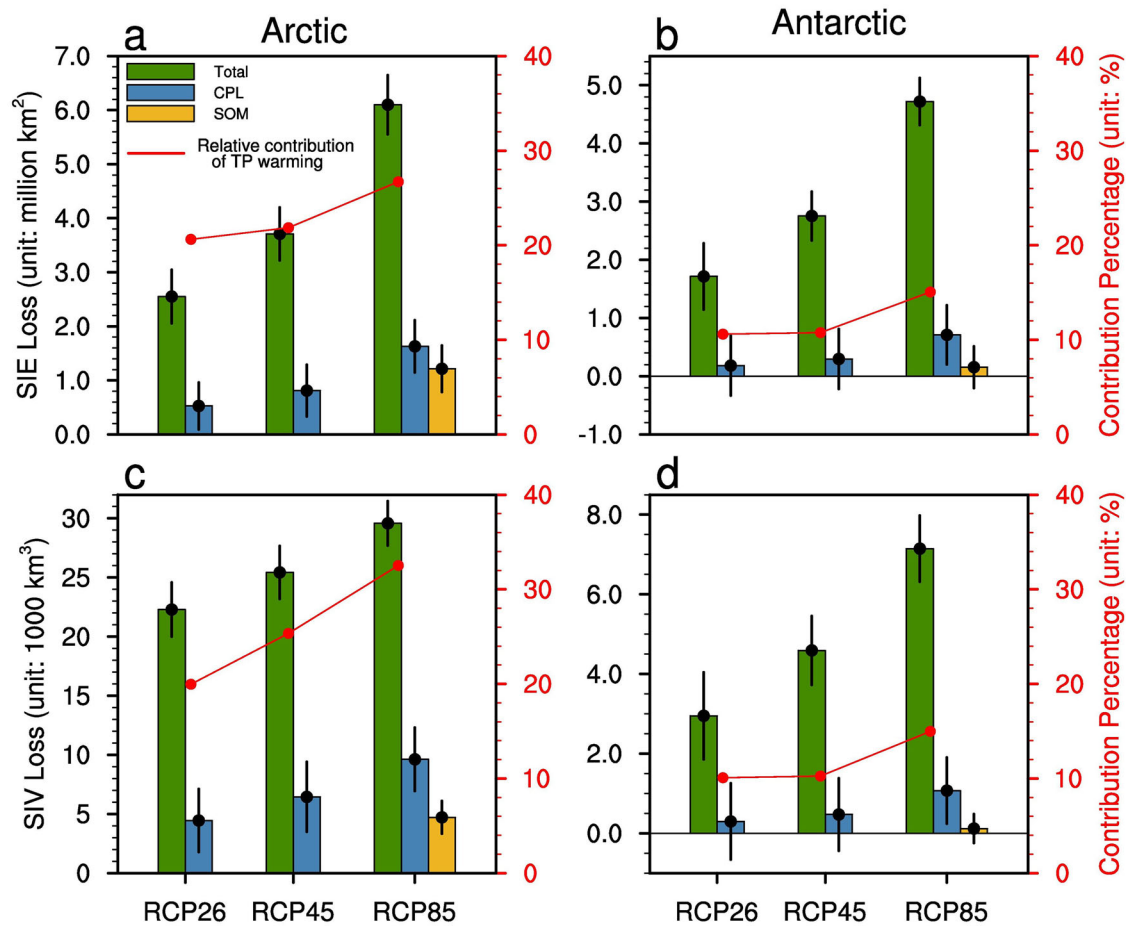


Fig. 3 | Contribution of the TPA to sea-ice loss. a, b Annual-mean total sea-ice extent (SIE; million km²) loss (green bar; left Y-axis) and the components attributable to the TPA under RCP2.6 (left), RCP4.5 (middle), and RCP8.5 (right) scenarios, derived from the fully-coupled (blue bar) and partially-coupled CESM simulations using a slab ocean model (SOM; golden bar). **a, b** Results for the Arctic

and Antarctic, respectively. SOM simulations are only performed for the RCP8.5 scenario. **c, d** Same as (a, b), but for sea-ice volume (SIV; 1000 km³). Black dots and vertical lines indicate the mean and the range of one standard deviation. Red dots and lines represent the relative contributions of the TPA to total SIE and SIV loss under each scenario (%; right Y-axis).

nudged fully-coupled simulations, although the magnitude and spatial extent are smaller. Simulations based on both CESM and an idealized model show that the TPA stimulates a northeastward propagating Rossby wave train, with an anti-cyclonic and cyclonic center over the Northwest Pacific and Bering Sea, respectively (Supplementary Fig. 5). This circulation pattern promotes the northeastward temperature and moisture advection from Sea of Japan, through Bering Strait, into the Arctic (Supplementary Fig. 6). Besides, the extra-polar SST anomalies induced by the TPA (Fig. 6a) may also contribute to Arctic warming^{38,39}. The influence of the TPA on the global SST pattern and the subsequent effect on Arctic surface temperature is further discussed in Supplementary Discussions.

Finally, we examined the mechanisms through which the TPA contributes to Antarctic sea-ice loss. According to Fig. 4, a two-stage mechanism is hypothesized: first, the TPA warms the southern low-to-mid-latitude SSTs through enhancing southward oceanic heat transport; then, the southern low-to-mid-latitude SST warming drives large-scale atmospheric circulation anomalies, which ultimately induce Antarctic warming and sea-ice loss. We begin by addressing the warming of southern low-to-mid-latitude SST by the TPA (Fig. 6a). The TPA triggers counterclockwise streamfunction anomalies in the upper subtropical-tropical ocean (above 1000 m), indicating a deceleration of the northern and an acceleration of the southern branches of the subtropical cell (STC) (Supplementary Fig. 7a). Further decomposition reveals that this response is primarily driven by changes in the Pacific Ocean (Supplementary Fig. 7c). The accelerated southern branch of the Pacific STC promotes the southward transport of

warm tropical waters, aligning with the dominant role of the Pacific Ocean in the southward OHT seen in Fig. 4c. Additionally, the Atlantic Meridional Overturning Circulation exhibits a dipole response to the TPA: it weakens below 1000 m but strengthens above this depth (Supplementary Fig. 7b).

The TPA also induces a westerly anomaly over the tropical Pacific, which generates a cyclonic circulation anomaly over the southern subtropical Pacific (Supplementary Fig. 8a, b). This cyclonic anomaly leads to the local positive surface wind curl anomalies ($\nabla \times [\vec{\tau}/(\rho f)]$, where $\vec{\tau}$, ρ and f denote wind stress vector, sea water density and the Coriolis parameter $f = 2\Omega \sin \varphi$, with Ω and φ denoting the angular velocity of Earth's rotation and latitude, respectively; Supplementary Fig. 8c). According to the relationship between surface wind stress curl and Ekman transport divergence ($\nabla \cdot \vec{U}_E = \vec{k} \cdot \nabla \times [\vec{\tau}/(\rho f)]$, where $\vec{U}_E$ and $\vec{k}$ denote Ekman transport and unit vector in vertical direction)⁴⁰, positive surface wind curl corresponds to local Ekman upwelling, that is, stretching of water column. Based on the theorem of potential vorticity conservation ($\frac{f}{D} = \text{constant}$, assuming negligible relative vorticity, where D denotes depth)⁴⁰, in the Southern Hemisphere, the stretching of the water column could lead to the southward Sverdrup transport. This is consistent with the strengthening southern branch of the Pacific STC found in Supplementary Fig. 7c, which facilitates the southward transport of warm tropical waters into the southern low-to-mid latitudes, potentially contributing to Antarctic warming and sea-ice loss.

Next, we consider how the southern low-to-mid-latitude SST anomalies lead to Antarctic warming. Ocean heat budget analysis (see Supplementary

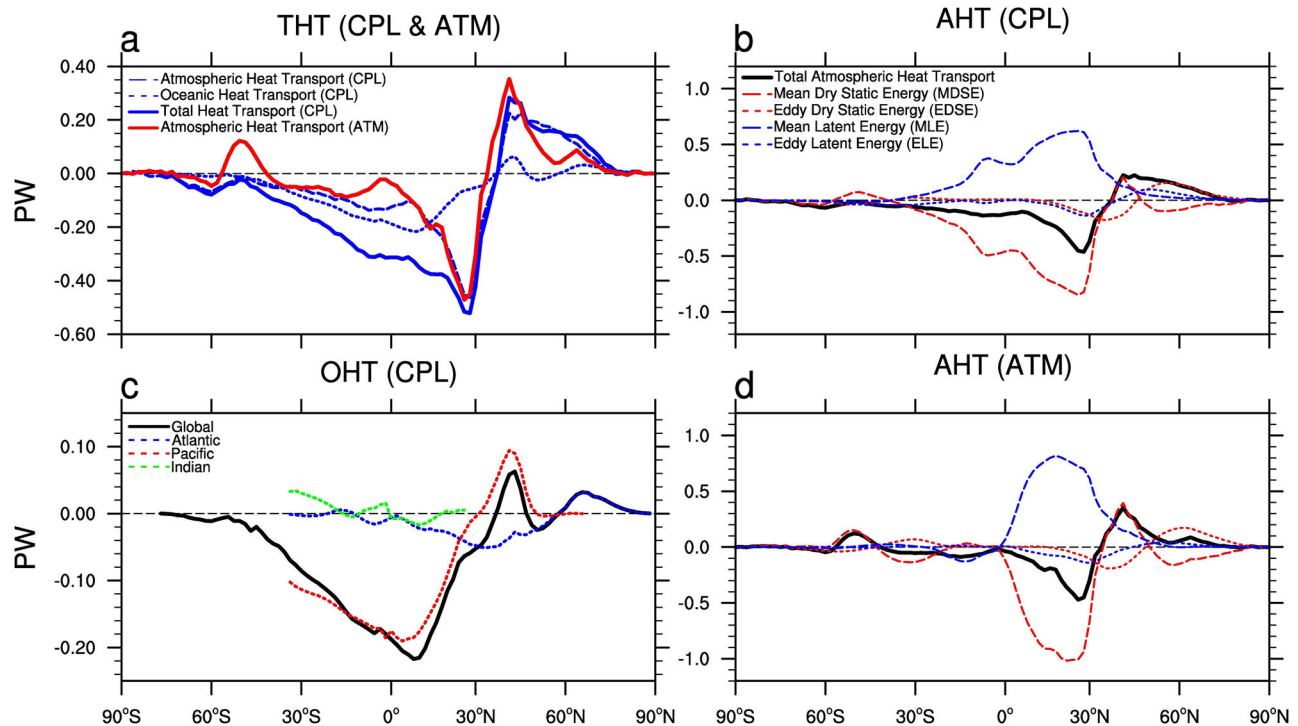


Fig. 4 | Response of northward heat transport to the TPA. **a** Response of total annual-mean northward heat transport (THT; petawatts, PW) to the TPA, derived from both TP-nudged and sea-ice-nudged (hereafter TP+ sea-ice-nudged) fully-coupled CESM simulations (TP_RCP85_fixaa minus TP_HIST_fixaa; blue solid line, representing the sum of atmospheric and oceanic heat transport—AHT and OHT) and from atmosphere-only simulations (TP_RCP85_ATM minus TP_HIST_ATM; red solid line, AHT only). Blue dashed and dotted lines represent the AHT and OHT components, respectively, derived from the TP+sea-ice-nudged fully-

coupled simulations. **b** Response of annual-mean northward AHT to the TPA (black solid line), along with its decomposition into mean and eddy components (long and short dashed lines), and further into dry static and latent energy transport (red and blue lines), derived from the TP+sea-ice-nudged fully-coupled simulations.

c Response of global annual-mean northward OHT to the TPA (black solid line), with contributions from the Atlantic (blue dashed), Pacific (red dashed), and Indian (green dashed) Oceans, derived from TP+sea-ice-nudged fully-coupled simulations. **d** Same as (b), but based on atmosphere-only simulations.

Methods) shows that the dominant contributor to SST warming around the Antarctic Peninsula, where the TPA-induced warming maximizes (Fig. 6a–c), is the thermodynamic process (Supplementary Fig. 9b) driven by surface net radiation, rather than ocean dynamical processes such as horizontal advection (Supplementary Fig. 9a). A more detailed decomposition shows that the reduction in surface upward turbulent heat fluxes (i.e., latent and sensible heat loss) is the primary driver of local SST warming (Supplementary Fig. 9c–e). This implies that the TPA-induced SST anomalies promote southward atmospheric warm advection, which in turn warms the surface by suppressing upward turbulent heat fluxes^{41,42}. Two additional atmosphere-only simulations driven by the TPA-induced global (Fig. 6a) and southern low-to-mid-latitude SST anomalies (Supplementary Fig. 10a), respectively, were conducted. The atmosphere-only simulations forced by global SST anomalies well reproduce the warming around the Antarctic Peninsula (Fig. 6d), which is primarily attributable to the southern low-to-mid-latitude SST anomalies (Fig. 6e). All these simulations capture a similar atmospheric circulation pattern, namely, a high-pressure center over the Weddell Sea and a low-pressure center over the Bellingshausen Sea (Fig. 6b–e). The resulting southward warm air advection between these centers promotes local surface warming and sea-ice loss. The SST forcing over 50°S–20°N is further decomposed into 6 subdomains (Supplementary Fig. 10d–i), driven by which 6 atmosphere-only experiments are performed (Supplementary Tab. S2). Consistent with previous literature^{34,43,44}, the SST anomalies over the tropical Indian (negative Indian Ocean Dipole-like pattern; Supplementary Fig. 10e) and Atlantic Ocean (Supplementary Fig. 10d) induce a similar circulation and surface warming pattern to those driven by the SST forcing over 50°S–20°N (Supplementary Fig. 11a, b). However, the El Niño-like SST pattern (Supplementary Fig. 10f) leads to a high-pressure center dominating the western part of the Antarctic, unfavorable for the

southward warm air advection towards the Antarctic Peninsula (Supplementary Fig. 11c). In addition, the SST anomalies over the South Atlantic (Supplementary Fig. 10g) and South Pacific (Supplementary Fig. 10i) could also contribute to the Antarctic warming (Supplementary Fig. 11d, f), while the SST anomaly over South Indian Ocean (Supplementary Fig. 10h) makes a minimal contribution (Supplementary Fig. 11e).

Discussion

This study quantitatively assesses the contribution of the TPA to Arctic and Antarctic sea-ice retreat. Our results indicate that TPA strongly accelerates polar sea-ice retreat at a rate dependent upon the level of global warming. Specifically, the relative contribution of TPA to Arctic sea-ice loss increases from ~20% under low-emission scenarios to ~30% under high-emission scenarios, and from ~10% to ~15% for its Antarctic counterpart.

In the Northern Hemisphere, the TPA enhances the meridional temperature gradient over the northern mid-to-high latitudes, strengthening the poleward-propagating eddies. These eddies transport additional heat and moisture into the Arctic, promoting surface warming and sea-ice decline. In the Southern Hemisphere, the TPA induces Antarctic sea-ice loss mainly through a two-stage ocean-atmosphere coupled pathway: first, the TPA enhances southward OHT and warms the southern low-to-mid-latitude SSTs; then, the southern low-to-mid-latitude SST anomalies induce large-scale atmospheric circulation anomalies, which ultimately lead to Antarctic warming and sea-ice loss. Figure 7 briefly illustrates the above-mentioned mechanisms.

Given its severe climate and social impacts, attribution of the observed and projected polar sea-ice retreat has become a hot topic in recent decades. Previous literature revealed that, except for local feedbacks (albedo feedback, lapse-rate feedback)^{45,46}, extra-polar forcings also

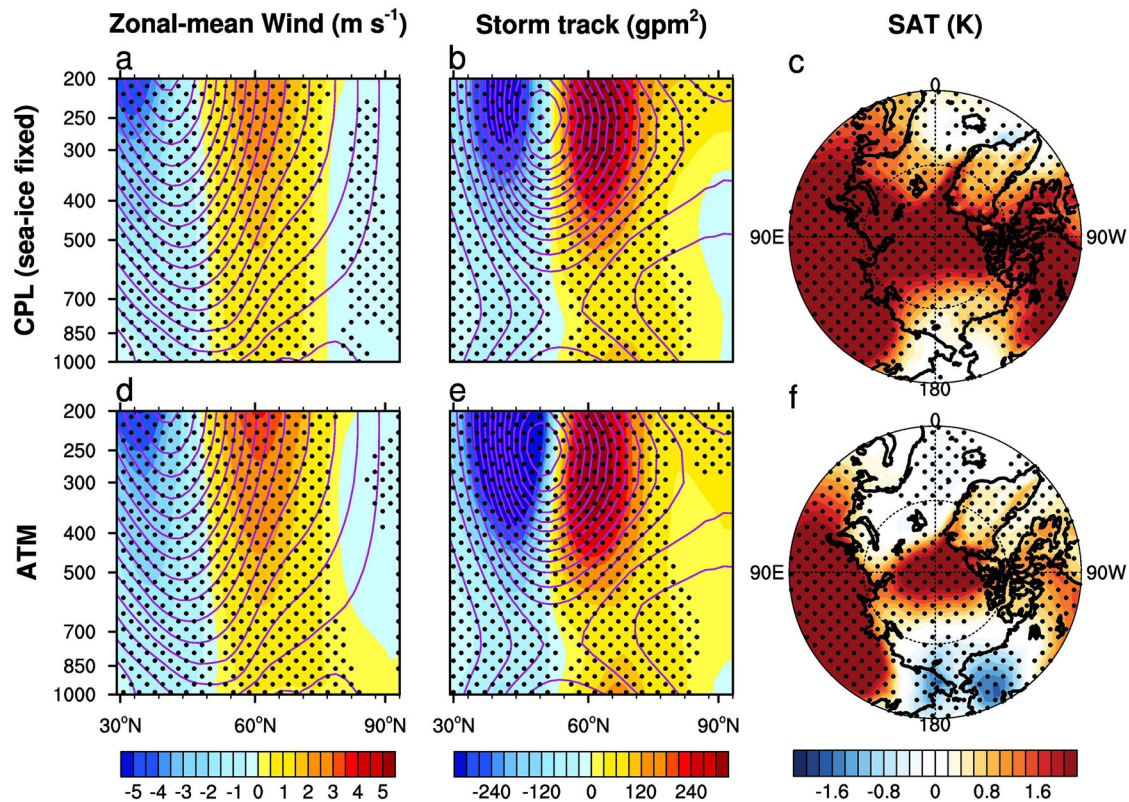


Fig. 5 | Boreal autumn atmospheric circulation responses to the TPA. Responses of boreal autumn (September–October–November) (a) zonal-mean wind (m s^{-1}), (b) storm track activity (gpm^2), and (c) near-surface temperature (K) to the TPA, derived from the TP+sea-ice-nudged fully-coupled simulations (TP_RCP85_fixaa minus TP_HIST_fixaa). d–f Same as (a–c), but for the atmosphere-only simulations (TP_RCP85_ATM minus TP_HIST_ATM). Purple contours in (a, b, d, e) show the

climatological autumn-mean values based on ensemble-mean historical simulations (1986–2005; HIST), with solid/dashed lines indicating positive/negative values, respectively. Black stippling indicates regions where anomalies are statistically significant at the 95% confidence level based on a grid-point-wise bootstrap resampling statistical test.

contribute to polar sea-ice retreat. In particular, tropical SST changes are found to be key drivers of polar sea-ice changes^{47–50}. Part of the mechanisms proposed in this study are built upon their findings, and we further extend the causal linkage to include the TPA. Most importantly, we quantified the relative contribution of the TPA to the polar sea-ice retreat, which turns out to be non-negligible. Moreover, our findings could help deepen our understanding of the potential causes of the emerging three-pole coupling in a warming world⁵¹. In addition, whether the TPA also contributes to the drastic Arctic sea-ice retreat and the alarming regime shift from stable to rapidly declining Antarctic sea-ice in recent decades, similar to this study, or not, deserves a deeper investigation in the future. By using the atmosphere and sea-ice nudging techniques, this study mainly focuses on the one-way impact of the TPA on polar sea-ice. However, recently, a growing body of literature indicates a two-way tele-connection between the plateau and polar regions^{51–54}. We hypothesize that this two-way tele-connection could further boost the plateau warming and polar sea-ice loss, which warrants further investigation in the future. A key potential caveat of this study concerns the nudging methods used here, which should be interpreted with a degree of caution. It has been argued that nudging introduces artificial heat into the model, which might lead to spurious signals, stemming from this artificial heating, rather than the TP warming or sea-ice loss^{55,56}. However, this spurious effect is challenging to quantify and/or reduce, requiring new modeling approaches.

Methods

Model description

The simulations in this study were conducted using the CESM (version 1.2.0)⁵⁷. CESM consists of several component models: the Community

Climate Model 5 (CAM5) for atmosphere, the Community Ice Code 4 (CICE4) for sea-ice, and the Parallel Ocean Program 2 (POP2) for ocean. Simulations that couple the atmosphere, ocean, and sea-ice components are referred to as fully-coupled runs.

In addition to the fully-coupled simulations, two additional types of experiments are performed. The first is a set of partially-coupled simulations, in which the full ocean model (POP2) is replaced by a single-layer SOM⁵⁸, while retaining the atmosphere and sea-ice components. In the SOM ocean is treated as motionless but well-mixed throughout its depth by prescribing the mixed-layer depth and ocean heat transport convergence. Therefore, in this model, only energy exchange upon the ocean-atmosphere interface is considered, and no ocean circulation changes will occur. The second is a set of atmosphere-only simulations, using CAM5 with prescribed SST and SIC boundary conditions. The horizontal resolution used in this study is $1.9^\circ \times 2.5^\circ$ (latitude $\times$ longitude).

Simulation scheme

A total of 14 experiments were conducted using CESM to isolate and quantify the relative contribution of the TPA to polar sea-ice loss, as is shown in Table 1. The experimental design follows a three-step framework:

- (1) Fully-coupled Transient Simulations: four fully-coupled transient simulations were performed, driven by the climate forcings (greenhouse gas concentration, aerosol emissions, and so on) of CMIP5 historical (1850–2005) and three future scenarios (2006–2100), namely, RCP2.6, RCP4.5, and RCP8.5, respectively;
- (2) Branched Transient Simulations: from these transient simulations, five-member ensembles of 20-year transient experiments were branched at two time points: (i) 1986, to represent the present-day climate (1986–2005, denoted as HIST), and (ii) 2080, to represent

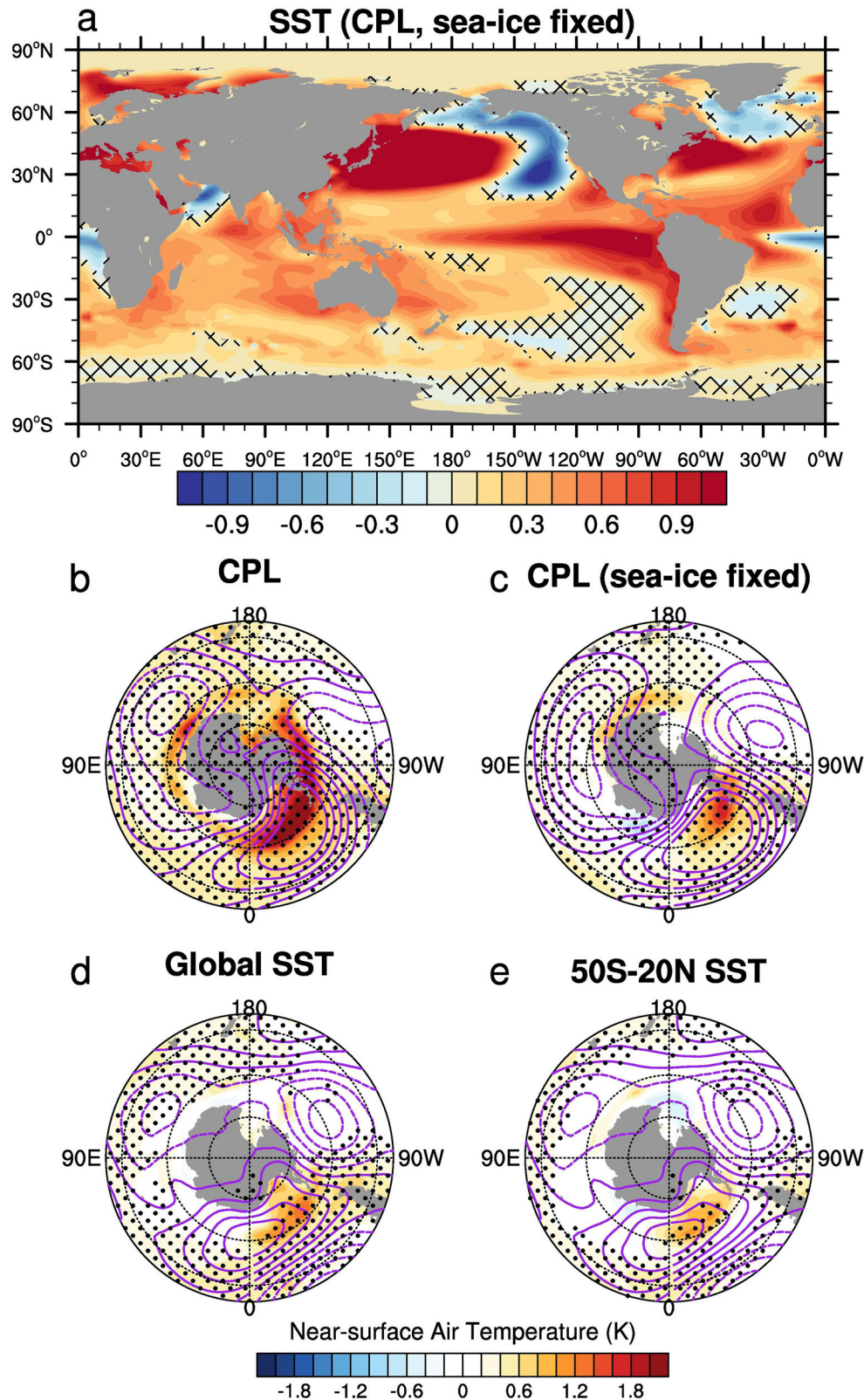
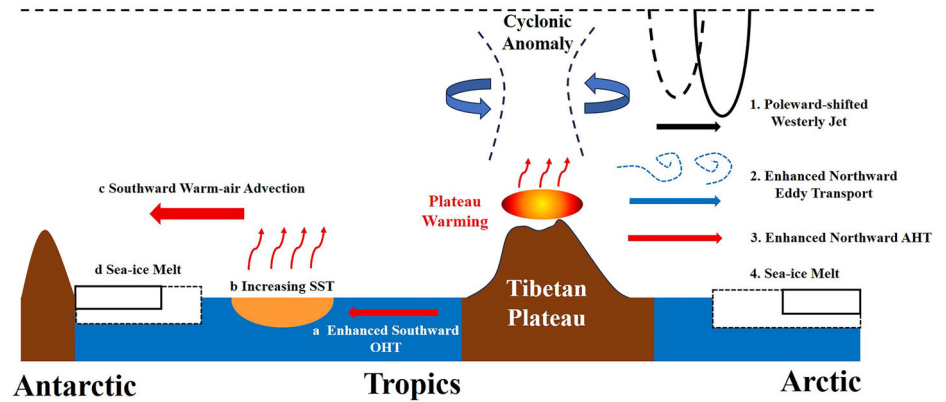


Fig. 6 | Global SST anomalies and the subsequent influence on Antarctic warming. **a** Responses of austral winter (June–July–August) sea-surface temperature (SST; shading; K) to the TPA, derived from the TP+sea-ice-nudged fully-coupled simulations (TP_RCP85_fixaa minus TP_HIST_fixaa). Cross-hatching indicates regions where anomalies are not statistically significant at the 95% confidence level based on a grid-point-wise bootstrap resampling statistical test. Responses of austral winter near-surface temperature (shading; K) and 500-hPa geopotential height (with zonal mean removed; contours; gpm) to the TPA, derived from the **(b)** sea-ice-free-

running (TP_RCP85 minus TP_HIST) and **c** sea-ice-nudged (TP_RCP85_fixaa minus TP_HIST_fixaa) fully-coupled simulations. **(d, e)** Same as **(b, c)**, but for the atmosphere-only simulations driven by global SST anomalies **(a)** and those over the southern low-to-mid latitudes (50°S–20°N; Supplementary Fig. 10a), derived from the TP+sea-ice-nudged fully-coupled simulations. Black stippling indicates regions where anomalies are statistically significant at the 95% confidence level based on a grid-point-wise bootstrap resampling statistical test. For the clarity of the figure, different marking schemes of statistical significance are applied for **(a–e)**.

Fig. 7 | Dynamical mechanisms of how the TPA induces polar sea-ice loss. Schematic diagram of the underlying physical processes through which the TPA causes polar sea-ice loss. Number and letter labeling denotes the Arctic and Antarctic pathways, respectively.



future conditions under RCP2.6, RCP4.5, and RCP8.5 (2080–2099). Each ensemble member was initialized with slight perturbations in the atmospheric temperature field ($\sim 1 \times 10^{-14}$ K) to account for internal variability;

(3) TP-nudging Time-slice Simulations: ten additional time-slice experiments were conducted that impose present-day and projected future atmospheric fields over the TP using the atmospheric nudging technique. These simulations allow for controlled assessment of the TP's influence on sea-ice evolution under different climate scenarios. Note that the 20-year transient simulations mentioned in (2) are restarted from the long-time fully-coupled simulations in (1). That is, theoretically, long-time ocean adjustment is also considered in these simulations, similar to the 200-year TP-nudged fully-coupled experiments, which makes them comparable.

For the nudged time-slice simulations, 3-h output of air temperature, horizontal wind, and surface pressure from the HIST and RCP2.6/4.5/8.5 simulations are used as reference fields. These fields were used to nudge the atmospheric fields over the TP towards their respective climatological states: 1986–2005 for HIST and 2080–2099 for the future RCP scenarios. Nudging is applied every 3 model hours. The vertical extent of nudging was determined based on the vertical profile of annual-mean air temperature differences between the historical and future states, averaged over the TP (Supplementary Fig. 12a). The horizontal nudging domain is shown in Supplementary Fig. 12b. A nudging coefficient was used to specify the strength of nudging, with a value of 0 representing free-running conditions and 1 indicating full nudging. Over the TP, the nudging coefficient was set to 1 below 100 hPa and linearly reduced to 0 at 50 hPa, creating a vertical buffer zone. Due to the complex topography of the TP, no horizontal buffer zone was applied.

In contrast to earlier studies that imposed artificial surface heating over the TP^{19–21}, our approach induced the full vertical extent of the TP warming. This choice reflects the vertically extensive nature of the TP warming, which could exert broader and more pronounced climatic impacts, similar to those observed under Arctic amplification^{59–61}. The vertical temperature profiles derived from the nudged simulations closely match the reference profiles, confirming the effectiveness of the nudging scheme (Supplementary Fig. 12a). For further details on the nudging methodology, see Peings et al.⁶² and Xu et al.^{63,64}.

Because sea-ice loss itself can strongly influence global climate^{33,65,66}, an additional pair of fully-coupled simulations (TP_HIST_fixaa and TP_RCP85_fixaa) was conducted with Arctic and Antarctic sea-ice nudged toward the historical state. These simulations employed a state-of-the-art hybrid sea-ice nudging technique⁶⁷, combining direct sea-ice nudging for SIC⁶⁶ and ghost-flux nudging for SIT⁶⁸. According to Audette et al.⁶⁷, the best combination of nudging timescale for both poles is 1 day for SIC and 5 days for SIT. To ensure mass conservation, the model was supplemented with additional freshwater fluxes and equivalent water mass from sea-ice melt.

For all these simulations, the last 100 years were used for analysis. Spin-up periods of 100, 50, and 10 years were discarded for the fully-coupled, SOM, and atmosphere-only simulations, respectively. Although some might suggest that hundreds, even thousands, years of spin-up is essential for the ocean to reach a quasi-equilibrium state^{69–71}, some others applied a 100-year, or even shorter, spin-up time^{33,72,73}. In this study, we found that polar sea-ice response evolution has reached a quasi-equilibrium state in the last 100-year simulations (Supplementary Fig. 13), justifying the 100-year spin-up applied here. All remaining forcings were fixed at year-2000 levels. Note that SOM and atmosphere-only simulations were conducted only for the historical and RCP8.5 scenarios.

In addition, 11 atmosphere-only simulations were conducted to assess the climatic effects of SST anomalies induced by the TPA. Their simulations were forced by SST anomalies derived from the TP+sea-ice-nudged fully-coupled runs (TP_HIST_fixaa and TP_RCP85_fixaa), while all other external forcings were fixed at year-2000 levels. Each simulation was run for 33 years, with the first 3 years discarded as spin-up to ensure model stability. Only the final 30 years were used for analysis.

Two of these simulations were driven by the global SST fields from TP_HIST_fixaa and TP_RCP85_fixaa (Fig. 6a), respectively, and are referred to as TP_HIST_global and TP_RCP85_global. To isolate regional contributions, eight additional simulations were performed using SSTs from TP_HIST_fixaa, but with SSTs over specific ocean regions replaced by those from TP_RCP85_fixaa. Additionally, one simulation (TP_RCP85_50S–20N) was performed using SST anomalies over the entire region spanning 50°S to 20°N from TP_RCP85_fixaa, while maintaining TP_HIST_fixaa SSTs elsewhere. The nine targeted regions and corresponding simulation names can be found in Supplementary Tab. 2.

Meridional heat transport

The calculation methods for meridional AHT and OHT used in this study follow the procedures described in detail by Yang et al.⁷⁴ and are briefly summarized here. The total AHT is computed using the following equation:

$$\text{AHT} = \int_0^{2\pi} d\lambda \int_{p_t}^{p_s} \bar{a} v (c_p \theta + l_v q) \cos \varphi / g dp \quad (1)$$

where $\lambda, p, p_s, p_t, a, v, c_p, \theta, l_v, q, \varphi$ and g denote longitude, air pressure, lower and upper bounds of vertical integration, Earth's radius, meridional wind, specific heat capacity of dry air, dry potential temperature, latent heat of vaporization, specific humidity, latitude, and gravitational acceleration. The total AHT can be further decomposed into four parts, that is, MDSE, MLE, EDSE, and ELE, according to the following equations:

$$\text{AHT}_{\text{MDSE}} = \int_0^{2\pi} d\lambda \int_{p_t}^{p_s} \bar{a} c_p \bar{v} \bar{\theta} \cos \varphi / g dp \quad (2)$$

Table 1 | Simulation scheme of CESM experiments

Experiment name	Simulation period (year)	Forcing	Ensemble size	Ocean-atmosphere coupling	Nudging TP	Nudging sea-ice
HIST	Year 1986–2005	Historical	5	Fully coupling	No	No
RCP26	Year 2080–2099	RCP26	5	Fully coupling	No	No
RCP45	Year 2080–2099	RCP45	5	Fully coupling	No	No
RCP85	Year 2080–2099	RCP85	5	Fully coupling	No	No
TP_HIST	Year 1–200	Year 2000	1	Fully coupling	Yes	No
TP_HIST_fixaa	Year 1–200	Year 2000	1	Fully coupling	Yes	Yes
TP_HIST_SOM	Year 1–150	Year 2000	1	Partially coupling	Yes	No
TP_HIST_ATM	Year 1–110	Year 2000	1	No	Yes	No
TP_RCP26	Year 1–200	Year 2000	1	Fully coupling	Yes	No
TP_RCP45	Year 1–200	Year 2000	1	Fully coupling	Yes	No
TP_RCP85	Year 1–200	Year 2000	1	Fully coupling	Yes	No
TP_RCP85_fixaa	Year 1–200	Year 2000	1	Fully coupling	Yes	Yes
TP_RCP85_SOM	Year 1–150	Year 2000	1	Partially coupling	Yes	No
TP_RCP85_ATM	Year 1–110	Year 2000	1	No	Yes	No

$$\text{AHT}_{\text{MLE}} = \int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a l_v \bar{v} \bar{q} \cos \varphi / g dp \quad (3)$$

$$\text{AHT}_{\text{EDSE}} = \int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a c_p v \theta \cos \varphi / g dp - \text{AHT}_{\text{MDSE}} \quad (4)$$

$$\text{AHT}_{\text{ELE}} = \int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a l_v v q \cos \varphi / g dp - \text{AHT}_{\text{MLE}} \quad (5)$$

where overbar denotes monthly mean.

In addition, it should be noted that the above calculations are based on the p -coordinate, interpolated from the original CAM5 σ - p hybrid coordinate. This could lead to the non-conservation of mass:

$$\int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a v \cos \varphi / g dp \neq 0 \quad (6)$$

Therefore, meridional wind should be updated according to the following equation:

$$v^* = v - \int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a v \cos \varphi / g dp / \int_0^{2\pi} d\lambda \int_{P_t}^{P_s} a \cos \varphi / g dp \quad (7)$$

OHT is calculated based on the following equation:

$$\text{OHT}(\varphi, \theta_t, \theta_b) = \rho c_p \int_{\theta_t(\varphi)}^{\theta_b(\varphi)} (\Psi(\varphi, \theta) - \Psi(\varphi, \theta_b)) d\theta \quad (8)$$

where φ , θ , θ_t , θ_b , ρ , c_p , and Ψ denote latitude, ocean potential temperature, maximum and minimum potential temperature reached by a closed circulation at a latitude φ , sea water density, specific heat capacity of sea water, and meridional stream function.

Sea ice and storm track diagnostics

Arctic and Antarctic sea-ice extent (SIE) is calculated by summing the grid cell areas where SIC exceeds 15%, within the regions north of 30°N and south of 30°S, respectively. Sea-ice volume (SIV) is computed as the sum of SIT multiplied by SIC on each grid.

Storm track activity, from an Eulerian perspective, is quantified as the variance of daily geopotential height after applying a 2.5–6 days bandpass

filter⁷⁵. This metric captures synoptic-scale variability and is commonly used to diagnose mid-latitude storm track intensity.

Statistical significance test

A bootstrap resampling test is employed in this study to assess the statistical significance of the differences between two samples. Let A_1 and A_2 be the two samples with respective sizes P_1 and P_2 . From each sample, subsets of size p_1 and p_2 (where $p_1 \leq P_1$ and $p_2 \leq P_2$) are randomly drawn 1000 times. For each iteration, the difference between the resampled subsets is calculated, and the distribution of these differences is used to estimate the 95% confidence interval. The 2.5th and 97.5th percentiles of the resampled distribution are taken as the lower and upper bounds, respectively.

If zero lies outside this confidence interval, the difference between the two samples is considered statistically significant at the 95% confidence level. Otherwise, the difference is deemed not significant. For additional details on the method, refer to Gilleland⁷⁶. In this study, the resampling subset size is 10. Student t -test yields very similar testing results (not shown).

Data availability

The processed data (in NETCDF format) to reproduce figures in the main text⁷⁷ are available from <https://doi.org/10.6084/m9.figshare.31912854>.

Code availability

Source codes of the CESM1.2.0 model are available from <http://www.cesm.ucar.edu/models/cesm1.2/>. Modified source codes of the sea-ice hybrid nudging method are available from Audette⁷⁸.

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Author contributions

M.X., S.C.K., H.J.Y., and J.A.S. designed the project. M.X., Z.M.J., and Y.P. performed model experiments and data analysis. M.X., H.J.Y., and J.A.S. interpreted the data and results. J.H.Y., Y.L.H., X.T.C., and H.Y. contributed to the revision of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Zhenming Ji.

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